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Sensitiveness of Solid and Liquid Explosives:

Part 2: The Effect of Bubbles in Liquid Explosives in Bulk

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R. Pape and E. G. Whitbread

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EXPLOSIVES RESEARCH AND DEVELOPMENT ESTABLISHMENT

REPORT NO. 17/R/52.

Sensitiveness of Solid and Liquid Explosives: Part 2: The Effect of Bubbles in Liquid Explosives in Bulk.

by

R. Pape and E.G. Whitbread

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1. SUMMARY.

This report describes a preliminary investigation of the effect of small bubbles of air on the sensitiveness of liquid explosives in bulk. It has been established in two ways that bubbles can give rise to some increase in sensitiveness to shocks. Firstly, photographic studies of the initiation of explosion in the liquid have shown that the explosion sometimes commences at a bubble. Secondly, by means of the 'Gap' test method of controlled initiation, it has been proved that explosion in the liquid can be produced by a somewhat weaker shock when bubbles are present than with bubble-free liquid.

The order of magnitude of the sensitising effect of bubbles appears, however, to be much smaller in bulk liquids than in thin films. A given liquid explosive is in the same class of sensitiveness to shock, under the conditions of the present tests, whether it contains bubbles or is carefully "degassed". The results reported here were obtained with samples of about 100 gm. size in glass and steel tubes of about 1 inch diameter; these results cannot be extended with complete confidence to liquids in greater bulk, or under heavier confinement, until more is known about the factors influencing the strength of the shocks transmitted to liquids under the conditions of the gap test. Work has been started on this problem.

Further experiments have been made in which ethyl nitrate containing bubbles of air was suddenly pressurised to several hundred atmospheres. In some cases combustion was initiated, which caused pressure-bursting of the apparatus, but even when the pressure was increased from one to 500 or 600 atm. this effect did not occur with bubbles of less than 0.1 inch diameter.

2. INTRODUCTION.

It is now well established that the sensitiveness to impact of thin films of molten or liquid explosives is greatly increased if small bubbles of air or other gas are present in the liquid. The explanation generally accepted is that the bubbles are heated to a high temperature by adiabatic compression during impact, thus producing 'hot spots' at which the explosion begins. Bowden and his co-workers (1), who have studied this effect exhaustively, have reported that the impact energy necessary to initiate explosion in films of explosives such as nitroglycerine may be reduced several hundred-fold by the presence of entrapped bubbles. The method of investigation was to allow a striker to fall on to a small quantity of liquid resting on a plane surface; when it was desired to trap a bubble, a small cavity was drilled into the nose of the striker.

There has been little evidence to date, however, that effects of the same order of magnitude can be caused by bubbles in large masses of liquid explosive. The present work was undertaken to clarify this point, the practical importance of which is obvious. The general conclusion has been that bubbles can increase the sensitiveness to shock of large volumes of liquid by providing centres at which detonation may be initiated, but that the magnitude of the effect is very much less than in the case of thin films, so that a liquid explosive would be in the same class of sensitiveness, whether or not it contained bubbles.

Two main experimental techniques, which are described in Sections 3 and 4, have been developed. In the first, the liquid under test is subjected to the shock wave from an exploding tetryl charge, the shock wave being attenuated by passing through a layer of inert material (cardboard). The thickness of card-

/board

board required to prevent initiation of the liquid explosive is measured both in the presence and absence of bubbles. This method has been found to give a reproducible measure of the sensitiveness of the substance under test (2). A definite but rather small increase in sensitiveness due to bubbles in D.E.G.N. has been demonstrated, and photographs of detonations starting at a bubble have been obtained.

In the second technique, pressures up to 500 atmospheres have been applied to the bubble for times of the order of 10-15 milliseconds. This was achieved by subjecting the liquid, with a bubble trapped in it, to the pressure developed by burning a cordite charge in a closed space. Under these conditions it was found that, when the bubble exceeded a certain critical diameter, very mild explosions could be produced; these, however, were far less powerful than complete detonations, and it was thought that they were probably due to rapid combustion, with consequent rise in pressure beyond the bursting-pressure of the apparatus.

Two liquids have been used in the trials here recorded; viz. diethylene glycol dinitrate (D.E.G.N.) and ethyl nitrate. These were chosen because they are sufficiently sensitive to detonate under reasonable experimental conditions, but at the same time not too dangerous to be handled in fairly large quantity.

3. THE FIRST EXPERIMENTAL TECHNIQUE.

We shall first describe briefly (Section 3.1) some attempts to use falling weights as a source of impact energy for the study of the effect of bubbles. These attempts were unsuccessful because of the low reproducibility of results. We shall then describe (Sections 3.2 to 3.5) the technique, already briefly indicated in the introduction, by means of which reproducible results were obtained.

3.1 Falling Weight Initiation.

A number of charges of D.E.G.N. were filled into cylinders closed with pistons. These charges were subjected to impact from freely-falling weights which hit the pistons and compressed the liquid. Results were very erratic, it being quite common to observe a smaller percentage of initiations with a higher impact energy. Friction between the piston and the walls of the cylinder was probably largely responsible for this, and attempts were therefore made to eliminate friction. Among the devices tried may be mentioned the use of copper cylinders, the use of very loose pistons supported by shear wires, and the use of 'stepped' pistons, the narrower portion of which dipped vertically into the explosive, with a water-layer floating on the explosive to separate it from the wider portion of the piston, the latter fitting closely into the cylinder.

None of these methods gave satisfactory reproducibility. Moreover the production of cylinders and pistons of suitable quality would clearly have involved great expense, as large numbers would have been required to give significant results. The falling-weight technique was therefore abandoned.

3.2 The 'Gap' Test.

The apparatus used in this work is illustrated in Fig.1. The liquid explosive is contained in a cylindrical tube, with a very thin sheet of metal foil at the bottom, fixed on with 'Necol' varnish, to make the system liquid-tight. Underneath this foil is a stack of sheets of cardboard, each 0.05 inch

/thick

thick, and below this a 20-gram charge of tetryl, in the form of a cylindrical pellet of 1 inch diameter and about 1 inch long, pressed to a density of 1.5 gram per cc. Below the tetryl pellet a No.8 Briska detonator is fastened with its axis horizontal. The detonator, tetryl pellet, and card stack are held in place by an elastic band passing round 'horns' near the bottom of the cylinder containing the test charge. This cylinder may be of glass (as in the Figure) or of steel, and bubbles can be introduced, if desired, on the end of a T-shaped stick. Three holes, each of 1 mm. diameter and 1 mm. deep, are drilled in the flat end of the bubble-stick. When the test charge is cased in glass, it is easy to check visually that bubbles are actually trapped, as can be seen from the enlarged photographs in Fig.5.

It is usual to refer to the liquid under test as the 'acceptor', to the tetryl pellet as the 'donor charge', and to the card stack as the 'gap'.

The minimum number of cards in the gap required to prevent initiation of the acceptor varies, as would be expected, with the diameter of the acceptor charge and with the strength of the walls of the cylinder containing it. This is illustrated in the Tables 1 and 2, the acceptor being D.E.G.N. throughout.

TABLE 1.

D.E.G.N. as Acceptor in Steel Tubes.

Internal Diameter of Tube, mm.	Maximum Number of Cards for 4 Detonations in 4 Successive Trials.	Minimum Number of Cards for 4 Failures in 4 Successive Trials.
17	31	32
27	25	27
46	25	28

TABLE 2.

D.E.G.N. as Acceptor in Glass Tubes.

Internal Diameter of Tube, mm.	Maximum Number of Cards for 4 Detonations in 4 Successive Trials	Minimum Number of Cards for 4 Failures in 4 Successive Trials.
25	18	20
36	11	15
50	6	8

/The

The minimum number of cards required to give four failures in four successive trials, with a standard container tube for the acceptor charge, is reproducible and is termed the 'card value' of the acceptor; it has been used to draw up scales of relative sensitiveness for both solid and liquid explosives. In general, reproducibility is better, the smaller the diameter of the acceptor; but very narrow tubes must be avoided because detonation frequently fails to propagate in them, so that results are indeterminate. The 'gap' should preferably consist of square cards, of area at least 50 per cent greater than the cross-section of the acceptor charge. Reproducibility is rather better in steel tubes than in glass ones. For this reason the work on D.E.G.N. and ethyl nitrate was divided into two sections: quantitative work was carried out in steel tubes of 27 mm. bore (Section 3.3) and optical work of a qualitative nature was carried out in glass tubes (Section 3.4) which permitted high-speed photography of events taking place inside the acceptor charge.

3.3 Quantitative Work on D.E.G.N. and Ethyl Nitrate.

The charge case for the acceptor was in all cases a 9 inch length of 'electrical conduit' tubing, of 27 mm. bore and 2 mm. wall thickness (nominally $1\frac{1}{4}$ inch diameter). The card stack and donor charge were as described earlier in this report.

Work was first carried out on charges of D.E.G.N. which had not been specially 'degassed' but in which no bubbles could be seen. When desired, bubbles could be introduced on the end of a stick, as previously indicated. The following results were obtained with the bubbles, when present, in the bulk of the liquid and about 1 cm. from the bottom of the charge.

TABLE 3.

Results for D.E.G.N. in the Presence and Absence of Bubbles.

Condition	Maximum Number of Cards for 4 Detonations in 4 Successive Trials.	Minimum Number of Cards for 4 Failures in 4 Successive Trials.
1. Without introduced bubble.	25	27
2. With bubble.	28	30

It was found that the bubble-stick, with no bubbles entrapped, made no difference to the card value for D.E.G.N.

When the bubbles were at the bottom of the charge, resting on the metal foil, the reproducibility was a little poorer, but the effect of the bubbles was of the same order of magnitude (Table 4).

/Table 4.

TABLE 4.

Results for D.E.G.N. with Bubbles at Bottom of Charge.

Number of Cards in Gap.	Number of Detonations in 4 Successive Trials.
26	4
27	3
28	3
29	1
30	0

Some other methods of "fixing" the bubbles were tried; for instance in one experiment thin capillaries of glass of 1 mm. diameter and 4 to 5 mm. long, closed at one end, were sealed to the metal foil at the bottom of the acceptor with Necol varnish. The results were rather erratic, but no definite increase in sensitiveness could be detected.

An obvious criticism is that, although there were no bubbles in the D.E.G.N. visible to the naked eye, there may have been microscopic ones present, at which initiation could occur. To meet this objection attempts were made to prepare thoroughly gas-free D.E.G.N. It was found that when D.E.G.N. is placed in a shallow dish in a desiccator and the latter evacuated, considerable frothing occurs. If the vacuum is released, and the desiccator re-evacuated after about 15 minutes, frothing is again quite marked, which indicates that air dissolves in the liquid fairly rapidly at atmospheric pressure. An effort was made to develop a technique for filling the acceptor charge cases under vacuum, then covering the top of the D.E.G.N. with molten wax and allowing the wax to set before breaking the vacuum. However, a suitable wax could not be found.

The following method was finally adopted. The D.E.G.N. was thoroughly degassed in a shallow layer at a pressure not exceeding 10^{-3} mm.Hg. Immediately after breaking the vacuum the liquid was poured into bottles which it filled, and tight-fitting rubber stoppers were inserted in such a way that no air space was left. The liquid was taken to the firing point in these bottles; the charges were filled and fired as quickly as possible after the removal of the stoppers. The explosive was never exposed to the air for more than ten minutes. The card values obtained for D.E.G.N. prepared in this way were identical with those previously obtained for untreated D.E.G.N.

Similar experiments were made with ethyl nitrate. The card value, under the exact conditions described above, was 2, and was unaltered by the introduction of bubbles on a stick. Bubbles of the following diameters were tried: 0.04, 0.05, 0.07, 0.08 and 0.10 inch. This result, while showing that in this case also the effect of bubbles in the bulk liquid is small, is probably of less value than the result for D.E.G.N. This is because for gaps of fewer than five cards, there is reason to think that hot gases and fragments from the exploding donor charge make contact with the acceptor, so that the initiation of the latter may be partly chemical and not solely due, as with the larger gaps, to the effect of a shock wave. Further, the effect upon the shock strength of

/adding

adding one card to the gap is probably much larger in gaps of 1 or 2 cards than in gaps of 20 to 30 cards.

3.4 Optical Work on D.E.G.N.

The work described in the previous section was supplemented by high-speed photographic observation of the processes going on inside the acceptor charge. A high-speed mirror camera was used, the principle of operation of which is simple and well-known. The test charge is set up as in Fig.1 and an image of it is focussed on to a strip of film bent into a semi-circle. The axis of the image of the cylinder containing the acceptor charge will be referred to as the 'vertical' direction on this film. As a detonation wave travels through the charge, the image is moved horizontally over the film, at a known speed, by means of a rotating mirror. Hence the detonation wave, which is luminous, is represented by a bright line on the film, at an angle to the horizontal, and the velocity with which it moves can be calculated from the tangent of this angle, the speed of rotation of the mirror, and the geometrical constants of the apparatus. In effect, every photograph taken in this way has a horizontal axis representing time, and a vertical axis representing distance. Figs. 2 to 4 and 6 to 8 are photographs of this kind and the time and distance scales are marked on them.

If a charge of D.E.G.N. is fired, with a gap considerably smaller than that needed to prevent initiation, the result shown in Fig.2 may be obtained. At A there is a bright flash from the explosion of the donor charge; there is a luminous straight line AB, representing the passage of a detonation wave to the top of the acceptor charge at B. The bright portion above B represents "end-effects" caused by the hot luminous products of explosion escaping from the tube. To the right of AB there are luminous striations at a fairly small angle to the time-axis; these are caused by burning products thrown out of the sides of the charge, moving upwards more slowly than the detonation wave. At B a horizontal line is seen to run into AB; this is probably caused by light reflected from the meniscus at the top of the D.E.G.N. charge. In the present case the velocity of detonation is found, from the slope of AB, to be 6,380 metres per second.

However, in glass tubing D.E.G.N. often fails to give a clearly defined detonation as shown in Fig.2, especially when the gap is fairly near to that required to prevent initiation. Under such conditions the effects seen in Fig.3 may be produced. At A there is the flash from the donor charge, and at B end-effects can be seen. The existence of end-effects proves that explosion has passed through the tube, which is invisible to the camera except for a faintly luminous portion PQ (this is distinctly visible in the negative). Moreover, its speed, as judged roughly from the slope of APQB is about 2,000 metres per second, and therefore much lower than that of the detonation photographed in Fig.2. It is clear that Fig.3 depicts a "low-order detonation", such as is well-known to occur under certain conditions in D.E.G.N. and in other liquid explosives. These low-order detonations are often invisible to the mirror-camera, but their occurrence can be inferred from the presence of end-effects.

When the gap is increased to very near the point of failure of initiation, the phenomenon shown in Fig.4 may occur. The flash from the donor charge is again seen at A, and the end-effect at B. At a point P between the two, there is a small but distinct luminosity, indicating a disturbance in the interior of the acceptor charge, at a time later than the explosion of the donor. In view of what was described in Section 3.3 it is reasonable to suspect that no explosion was initiated between A and P, but that a detonation was initiated at a microscopic bubble at P; this faded into a low-order detonation which is

/not

not directly visible, though there is a faint luminosity to the right of PB from burning products. Several other photographs similar to Fig.4 have been obtained, and the apparent point of initiation P occurs at varying distances from the donor charge; this is consistent with the view that it represents initiation at a 'stray' bubble.

To confirm this supposition, the arrangement shown in Fig.1 was again set up, with the gap slightly in excess of that required to prevent initiation, and with bubbles inserted on the end of a stick. Fig.6 shows a typical photograph obtained under these conditions. The point P is found, by measurement, to coincide with the position of the bubbles introduced, and the luminous curved line from P, bending away from the vertical clearly indicates a high order detonation, initiated at the bubble, and fading in a very short distance into an invisible low-order detonation. The end-effect appears at B as before.

The question, whether there was an explosion before the shock from the donor charge reached the bubble, must be considered since it might be argued that in the experiments photographed in Figs. 4 and 6, an invisible low-order detonation travelled from A to P, and was momentarily converted into a high-order detonation at the bubble. Fig.7, obtained under very similar conditions to Fig.6, provides an answer to this question. The disturbance is again seen at P, which coincides with the point at which the bubble was introduced; but it is evident that the high-order detonation initiated at P travels in both directions. Clearly, therefore, the D.E.G.N. between A and P cannot have exploded before the high-order detonation commenced at P. Several similar photographs have been obtained; and indeed a further scrutiny of Fig.4 indicates that the same effect is found in that case. A close examination of the disturbance at P shows that it occurred simultaneously at two points close to each other, and spread from each in both directions. In no case has evidence of low-order detonation changing to high-order detonation at the bubble come to light, though the possibility of its occurrence under some conditions has not been completely excluded.

A final proof that detonation may be initiated at a bubble is provided by Fig.8, which records an experiment under rather different conditions. The apparatus was similar to that in Fig.1, except that the acceptor (D.E.G.N.) was contained in a perspex tube of rectangular cross-section instead of the usual glass cylinder. Bubbles were inserted on a stick as before. The system was illuminated from behind by a beam of light from a mercury arc and an optical condenser, and its shadow fell on to the plane side of a plano-convex lens. This shadow was photographed by the mirror-camera. The field of the camera was limited to a vertical strip of the acceptor in line with the bubble-stick, so that the latter cut off the light above a certain point; this gives rise to the dark line XP. The shock wave emerging from the gap appears as a dark line (AP), because when the D.E.G.N. or the perspex is compressed its refractivity is increased, and the light coming through it is deflected away from its previous optical path. The slope of AP gives the velocity of the shock as 1,250 metres per second. Proceeding from P horizontally to the right we reach a point Q, at a distance corresponding to a time interval of 40-45 microseconds, from which a low-order detonation QB sets out from the end of the bubble-stick and travels up the acceptor at 1,750 metres per second. In this case the low-order detonation is clearly visible to the camera, partly because the large plano-convex lens acted as a light-gatherer and increased the intensity of the image on the film, and partly because the writing speed was lower than in the previous cases.

It is not at present clear whether the line AP represents a shock wave in the perspex or in the D.E.G.N. itself. In spite of this uncertainty, however, three facts are definitely established by this experiment. Firstly, initiation occurred at the point where the bubbles were inserted; and, since the presence of the stick without bubbles has been shown not to produce initiations, the

/proof

proof that they are caused by the bubbles is conclusive. Secondly, no detonation occurred before the shock wave reached the bubble, for if it had done so it should be visible below the level of XP. Thirdly, the time interval represented by PQ, viz. 40-45 microseconds, gives an upper limit for the time between the arrival of the shock at the bubble and the commencement of the detonation; for if AP represents the shock in the D.E.G.N., PQ represents this interval exactly, while if AP represents a shock in the perspex, that in the liquid much reach the bubble later.

3.5 Assessment of the Attenuation Due to the Card Stack.

The work described in Sections 3.3, 3.4 establishes that bubbles may increase the detonability of bulk liquids by shock, by providing centres for initiation of explosion, and it further provides a quantitative estimate of the degree of sensitisation produced by bubbles, in terms of the empirical 'card value' measured by the 'gap' test. On general grounds it would be very difficult to believe that an increase of three cards in the thickness of the gap could correspond to a decrease of several hundred-fold in impact energy, such as Bowden and his co-workers have found for the sensitisation of thin gilms of liquid by bubbles. It is known, for example, that explosives which, from general experience, appear to be in the same class from the standpoint of sensitiveness, may have card values differing by considerably more than three cards. It is desirable, however, to know more precisely what a given change in card value means in terms of the pressure to which the acceptor is compressed by the shock wave emerging from the gap, and the time for which this pressure is applied to any given plane in the acceptor charge. The problem is not yet solved, but work is in hand to elucidate it, and the present position may be briefly indicated. Three lines of approach have been considered.

(a) The most direct method of measuring the impulse due to the emerging shock wave would be to use the Hopkinson pressure bar (3), by means of which the impulse could be converted into the momentum of a flying piece of metal and measured directly with a ballistic pendulum. Unfortunately, no pressure bar was available at the time of the investigations here reported; but one has now been obtained.

(b) The effect of varying the gap thickness has been compared with that of varying the diameter of the donor charge. The card value of D.E.G.N. has been determined for donor charges of tetryl with diameter varying between ½ inch and 1½ inch. All were of length 1 inch and density 1.5 gram per cc., and the acceptor charge case was in every instance steel 'conduit' tubing of 27 mm. bore. The results are given in Table 5.

TABLE 5.

Card Values for D.E.G.N. with Varying Donor Charge Diameter.

Diameter of Donor Charge, inches	Cross-Sectional Area of Donor Charge, square inches	Minimum Number of Cards for 4 Failures in 4 Successive Trials.
½	0.196	11
¾	0.442	21
1	0.785	27
1½	1.767	47

/If

If the logarithm of the cross-sectional area of charge is plotted against the card value, as in Fig.12, the first three points are found to lie on a straight line. The point for a $1\frac{1}{2}$ inch donor charge lies off this line, but this is readily understood since in this case the donor charge had a larger diameter than the acceptor. Hence, to increase the gap width by a given number of cards corresponds to changing the cross-section of the donor charge in a fixed ratio. In fact, the addition of 8 cards to the gap attenuates the shock to the same degree as reducing the donor cross-section by half, and addition of 3 cards to the gap corresponds to reduction of the cross-section by 23 per cent.

Unfortunately this method gives no direct information about the shock strength (i.e. the pressure ratio across the shock front, which is equal to the pressure behind the shock in atmospheres, since the pressure ahead of the shock is one atmosphere). If it were assumed that the shock strength is proportional to the cross-sectional area of the donor charge, for a fixed gap thickness and diameter of acceptor charge, then it would follow that an increase of gap thickness by 3 cards reduces the shock strength to 77 per cent of its original value. The shock strength required, in the presence of the bubble would be, therefore, about three quarters of that required to initiate D.E.G.N. without the bubble. However, such a simple assumption cannot be made with any degree of certainty at the moment.

(c) It is possible to determine the strength of the shock emerging from a card stack into a liquid by measuring the velocity of the shock, provided that the equation of state of the liquid is known at the pressures reached in the shock wave. Such data are available for water; the pressures corresponding to various shock velocities have been calculated and tabulated (4). A programme of work is now in hand to measure the velocities of these shock waves in water, by a photographic method similar to that used for the last experiment recorded in Section 3.4.

Some 'still' photographs have also been obtained of the shock waves in water, shortly after entering it from the card stack, using an Arditron flash bulb as a light source of very short duration. They show that the shock front, though slightly convex upwards, is almost planar. At present no information is available on the duration of the shock, i.e. on the time which elapses, after the shock front has reached a given point, before the pressure begins to fall markedly. It is hoped to develop a method for investigating this.

4. THE SECOND EXPERIMENTAL TECHNIQUE.

The results of Section 3 give a fair assessment of the effect of bubbles on the sensitiveness of liquids in bulk to shock waves, such as might be generated by the impact of solid bodies or by explosions in the neighbourhood. In all such cases, however, the bubble is likely to be under compression for a very short time. When liquid propellants are handled in rocket motor assemblies the pressurising of tanks, lines, etc. may lead to compressions of much longer duration, though the actual pressures reached are much lower than in shock waves resulting from explosions. A method of applying a sudden pressure to a liquid explosive and maintaining it for a much longer time was, therefore, devised. The duration of the high-pressure regime would be expected to make no difference to the probability of explosion, provided that it exceeds a certain minimum time needed for the hot compressed bubble to transmit its heat to the adjacent explosive (5). The final experiment of Section 3.4 depicted in Fig.8, suggests an order of magnitude for this 'critical' time for shock waves; for in this instance the whole process from the initial compression of the bubble to the commencement of detonation took not more than 40-45 microseconds.

/The

The apparatus used is illustrated in Fig.13. A pressure vessel B can be closed at the top by screwing in a sparking plug C with a close-fitting gasket. To the lower end of B is fitted a long J-shaped steel tube. The other, shorter, arm of the J-tube is closed with an 'Ermeto' joint; this has a stick A, which can carry a bubble at its lower end, fixed to it. A small cordite charge is burnt in B; this pressurises the whole system. Ethyl nitrate was used as the test liquid in all experiments.

The tests were carried out as follows: The sparking plug C and the bubble-stick were both removed, leaving the J-tube open at both ends. Sufficient ethyl nitrate was introduced to fill the tube to just below the level of the Ermeto joint. The bubble-stick was now inserted, trapping a bubble, till the joint was almost but not quite closed. Water was now pipetted on to the top of the ethyl nitrate layer at A till it overflowed, thus preventing the explosive from being caught in the screw threads, and the joint was closed. Next, water was run into the other limb at C to a known level, measured with a dipstick; the volume of free space left in B was known from a previous calibration. Finally, a weighed charge of sheet S.C. cordite, 0.03 inch thick, together with a weighed piece of igniter cambric and an electric safety fuze, were suspended by the fuze leads from the electrodes of the sparking plug; the latter was screwed in and the fuze was fired. The pressures developed were estimated by similar experiments in which a condenser gauge was inserted at A instead of the bubble-stick. Fig.11 shows a typical oscillographic pressure record, the horizontal row of marks along the top of the figure being time marks at intervals of 0.1 second. The pressure quoted in the text is not the absolute peak pressure, but that which persists for 10-15 milliseconds: in the case shown in Fig.11, 2,000 p.s.i. or 140 atmospheres. The calibration is only accurate to ± 50 atm. at best, but pressures above 500 atm. can be obtained, which exceed by a good margin those likely to be reached when rocket assemblies are pressurised.

By varying the size of the cavity in the end of the bubble-stick, it was possible to entrap bubbles of different diameters. The tests, which are recorded fully in Table 6, indicate that for a given final pressure there is a critical size of bubble, above which explosion may occur on compression; this is, of course, readily understood. Adams and Wiseman (5) have discussed this question.

TABLE 6.

Trials with Cordite Pressurising Apparatus.

Diameter of Bubble, inches	Final Pressure, atm.	Number of Trials	Number of Explosions
0.04	500 - 600	5	0
0.08	500 - 600	5	0
0.11	500 - 600	5	0
0.16	500 - 600	2	2
0.16	250	1	1
0.16	125	1	0
0.23	125	5	2

/The

The explosions recorded were mild, far below detonations in power. This can be inferred from the damage to the 'J-tubes', two instances of which are shown in Figs. 9 and 10 respectively. Fig. 9 shows the whole assembly, before and after firing, in one experiment; Fig. 10 shows the lower end of the J-tube, before and after firing, in another experiment. The degree of damage suggests that what took place was merely a rapid burning; the compression initiated combustion, which did not pass into detonation under the present conditions of confinement, but only caused a pressure-burst.

These experiments might be criticised on the grounds that (a) the internal diameter of the 'J-tubes' was fairly small (9/16 inch), whereas detonation is more readily initiated and propagated in wide tubes; and (b) that the ethyl nitrate used contained a small amount of water, which would slightly reduce its sensitiveness.

5. DISCUSSION AND CONCLUSIONS.

The experiments described in Section 3 establish that the presence of small air bubbles in bulk liquids may cause some increase in the sensitiveness of the liquids to shock waves. Using the 'gap' test, it has been found that the card value for D.E.G.N. (i.e. the number of sheets of cardboard, 0.05 inch thick which must be placed between the D.E.G.N. and an exploding charge of 20 grams of tetryl to prevent initiation of explosion in the D.E.G.N.) can be increased from 27 to 30 by the presence of a bubble, when the D.E.G.N. is confined in steel 'conduit' tubing of 27 mm. internal diameter and 2 mm. wall thickness. In addition, definite photographic evidence has been obtained that under some conditions an explosion, initiated by a shock wave in the liquid, starts at a bubble.

The increase in shock sensitiveness of bulk liquids caused by the bubble appears to be far smaller than the increase in impact sensitiveness produced by bubbles in thin films of liquid. A possible reason for the difference is that the time of compression of a bubble by a shock wave, in a large bulk of liquid, is probably much less than the time of duration of the high-pressure regime when a film of liquid is struck by a hammer on an anvil. In the latter case the time of compression is of the order of 200 microseconds; in the former it is not certainly known, but may well be less than 10 microseconds.

Adams & Wiseman (5) have devised a formula which gives the minimum duration of pressure pulse for initiation at a bubble to occur. The relation is:

$$t \sim \frac{10}{v^2 P} \qquad \text{.........................} \quad \underline{1}$$

where t = Minimum time (sec),

v = Linear flame velocity of explosive (cm/sec),

P = Pressure (atm).

For ethyl nitrate, v = 2 to 3 cm./sec. and, therefore, t is 2 to 4 milliseconds at P = 500 atm. and 8 to 16 milliseconds at P = 125 atm. These times are compatible with the experiments described in Section 4.

The effect of a change in card value on the strength of the shock transmitted through the card stack to the liquid has not yet been evaluated. In

/Section

Section 3.5 (b) it has been shown that under the present conditions of confinement, an increase in card value by 8 cards has about the same effect upon the shock as a twofold increase in the cross-sectional area of the donor charge. Thus, for example, the shock from a cylindrical tetryl charge of 1 inch diameter after passing through 11 cards, is more than sufficient to initiate explosion in the D.E.G.N.; it can be reduced to the point at which it just fails to initiate, either by adding 16 extra cards to the gap, or by reducing the area of the donor charge by a factor of 4 (Table 5). If we assume that the shock strength S (i.e. the pressure ratio across the shock front) is a function of the form:

$$S = k.A^n.f(C) \quad \dots\dots\dots\dots\dots\dots \underline{2}$$

where k and n are constants,

A is the cross-sectional area of the donor charge,

amd C is the card value,

then the above results require that f(C) shall be exponential in form:

$$f(C) = e^{-\lambda C} \quad \dots\dots\dots\dots\dots\dots \underline{3}$$

since a fixed increment in C has the same effect as an increase in A by a given ratio.

The effect of a change of C by 8 cards is equivalent to a twofold change in A and therefore to a change in S by a factor of 2^n. Hence a change of C by 3 cards (the maximum effect ever produced in D.E.G.N. by the presence of a bubble) would change S in the ratio $2^{3n/8}$. If n = 1 (a quite likely value), this ratio is 1.3; if n = 2 it is 1.7. It is clear, therefore, that the effect of 3 cards on the shock strength is not to alter its order of magnitude for any reasonable value of n. It follows that, as stated above, a stray bubble in D.E.G.N., though it produces some increase in sensitiveness, does not put the liquid into a different class of sensitiveness.

In the above discussion, however, no account has been taken of the effect of either diameter or the confinement of the acceptor charge upon the strength of the shock passing into it from the card stack. A good deal of work has been done, using the 'gap' test, with a larger acceptor diameter and confinement; this is to be described in a subsequent report. The formulae 2 and 3 above do not fit at all well under these new conditions. The fact that the same formulae will not fit in both cases obviously suggest that one or more variables which influence the shock strength have been left out of account; and these may well be the diameter and confinement of the acceptor. This question can only be settled by a full study of shock pressures by the measurement of the velocities of shocks emerging from the various card stacks into liquid. The Hopkinson pressure bar will also provide useful information, though not of such direct importance, since in this technique the shock is transmitted from the cards to a metal bar, not to a liquid under confinement. Until further information is available, the results of the present investigation cannot be extrapolated without reserve to estimate the effect of bubbles on the sensitiveness of liquids in much larger bulk or under much heavier confinement than those employed here.

The work described in Section 4 shows that small bubbles in the bulk of a liquid are unlikely to initiate combustion or explosion when the liquid is pressurised as for instance in a rocket assembly. Using ethyl nitrate, no effect was produced with bubbles of less than 1/10 inch diameter, even when pressurised to over 500 atmospheres. There is, however, a definite danger from larger pockets of air, such as may be trapped between the liquid and metal

/parts

parts, e.g. in valves or at bends in pipes. Sudden pressurisation might lead to combustion at such pockets; under light confinement a pressure burst would probably occur, but under heavy confinement the burning might pass over to detonation.

6. ACKNOWLEDGMENTS.

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S.No.280.
M.No.19/52.BM.

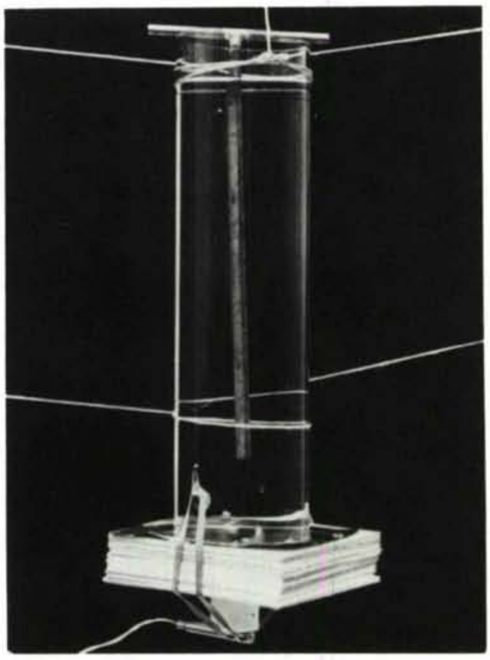


Fig I

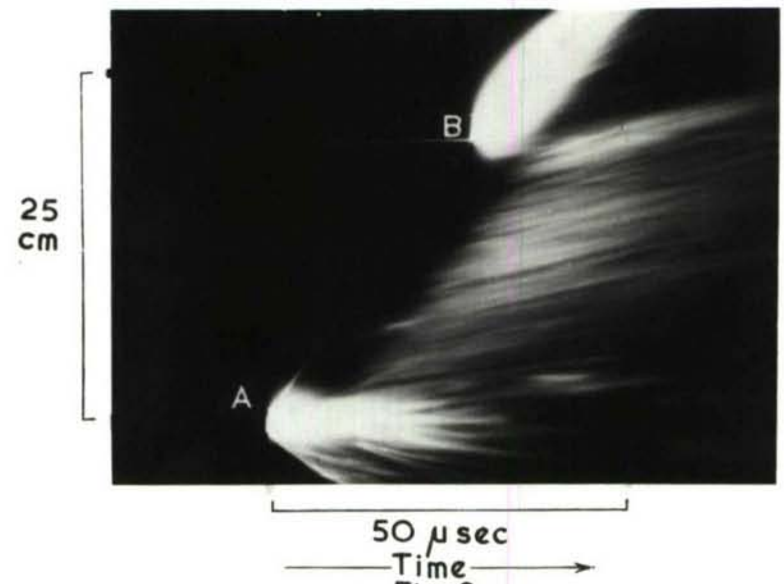


Fig 2

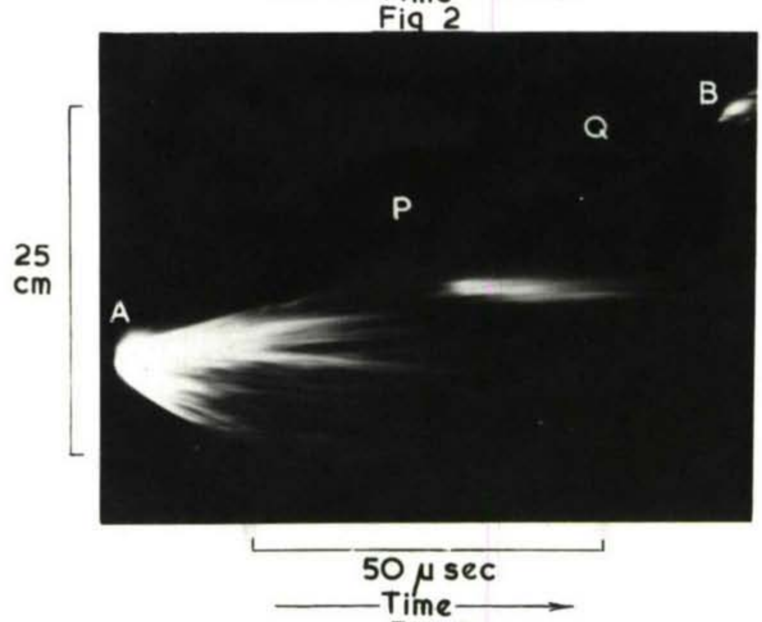


Fig 3

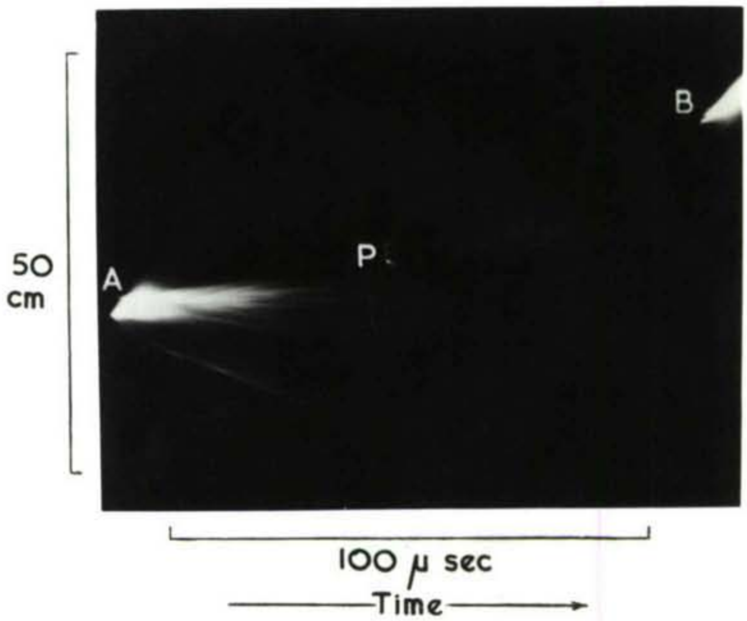
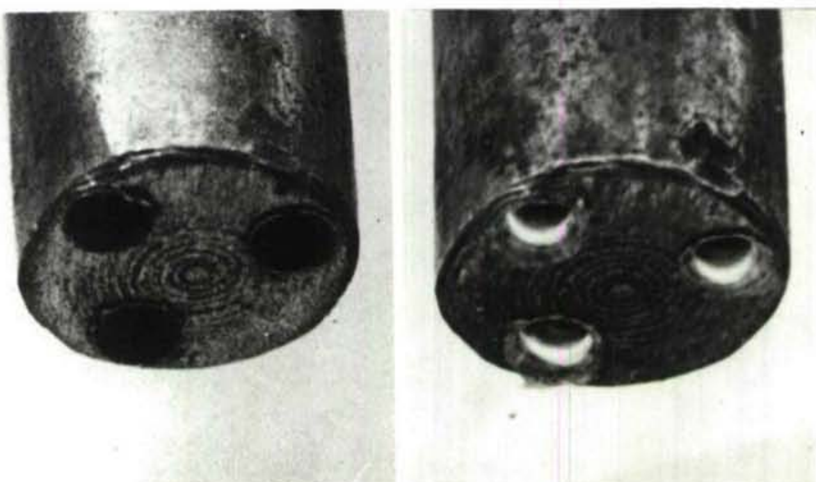


Fig 4



(a) (b)

Fig 5

Enlarged Photographs of End of Bubble-Stick

(a) Without Bubbles (b) With Bubbles

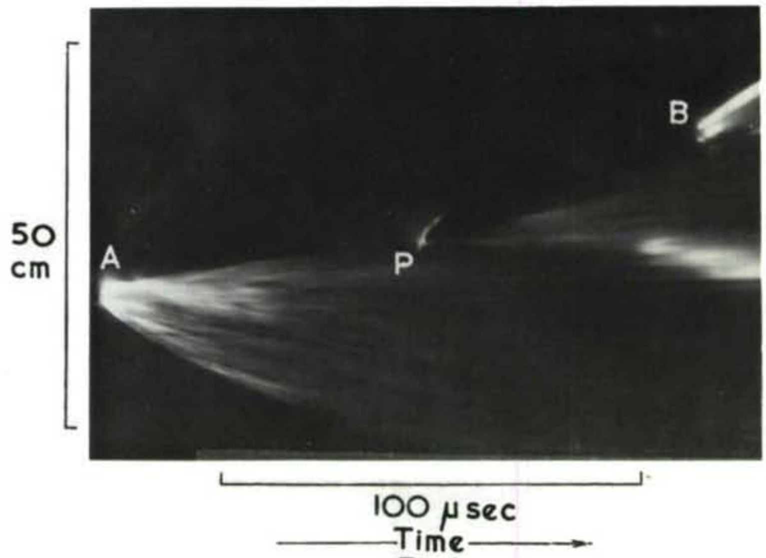


Fig 6

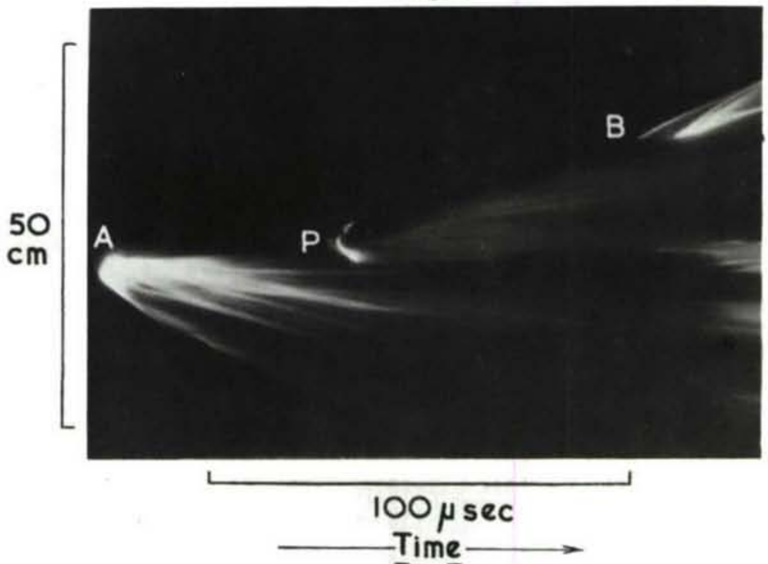


Fig 7

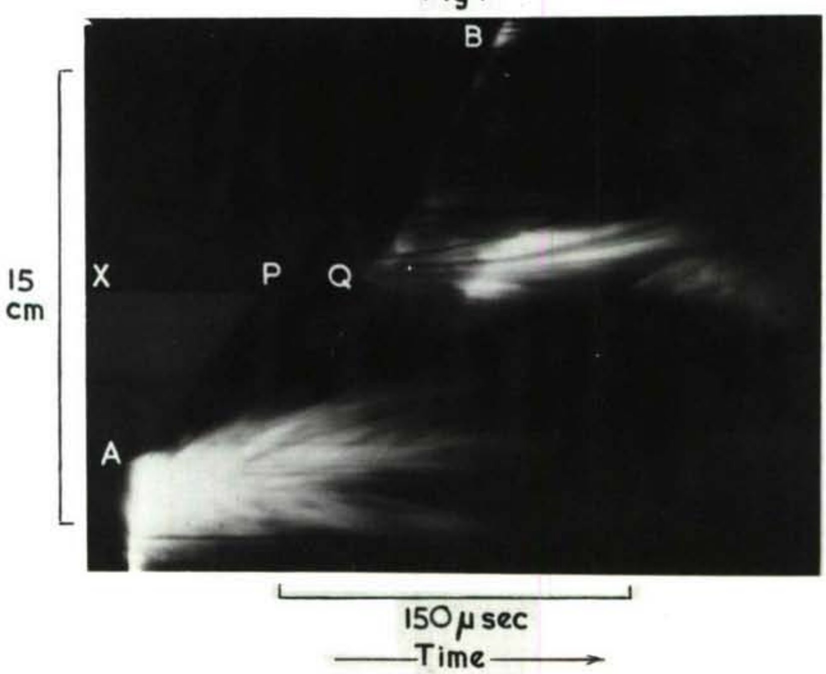
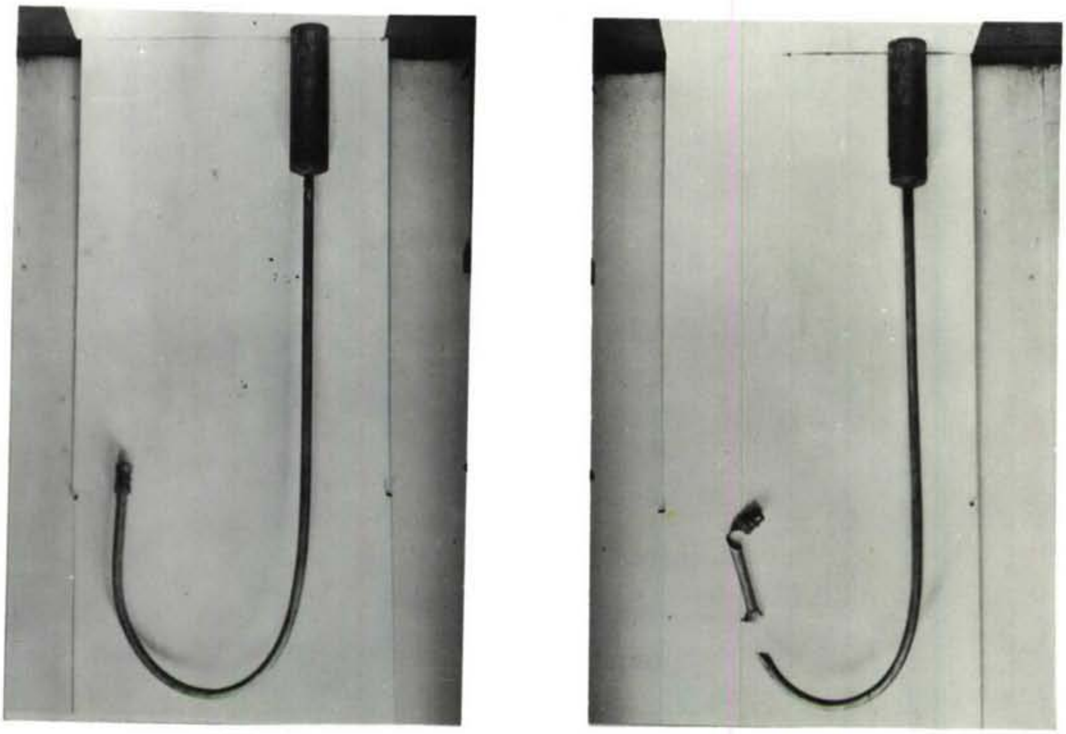


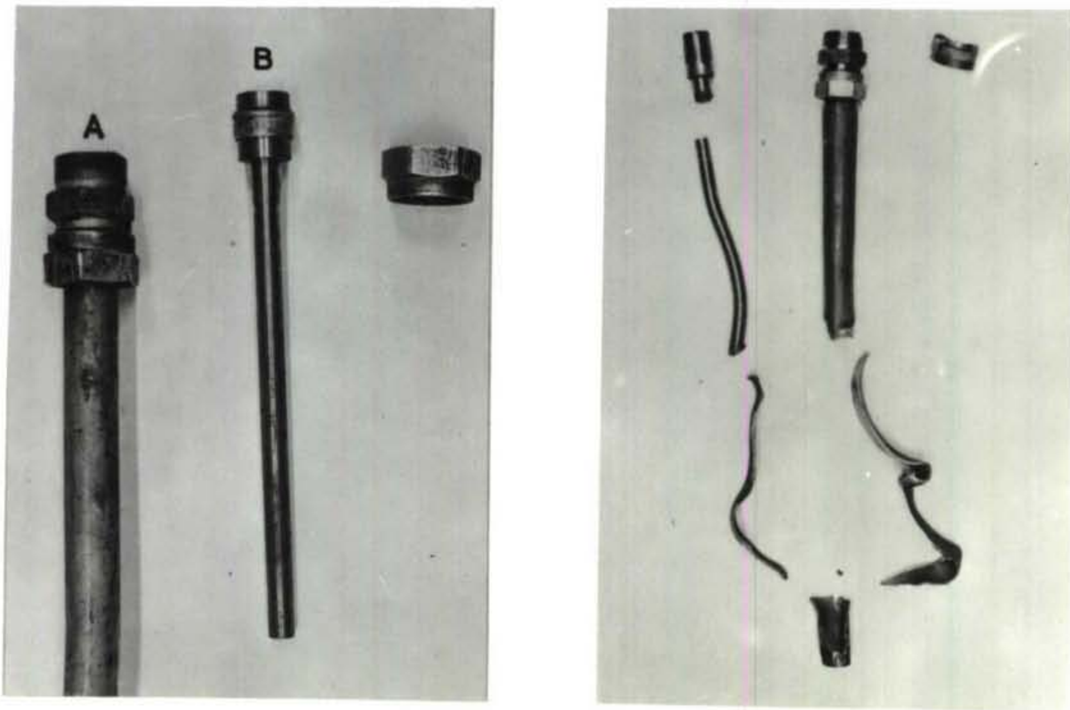
Fig 8



(a) (b)

Fig 9

Effect of Mild Explosion of Ethyl Nitrate in J-Tube

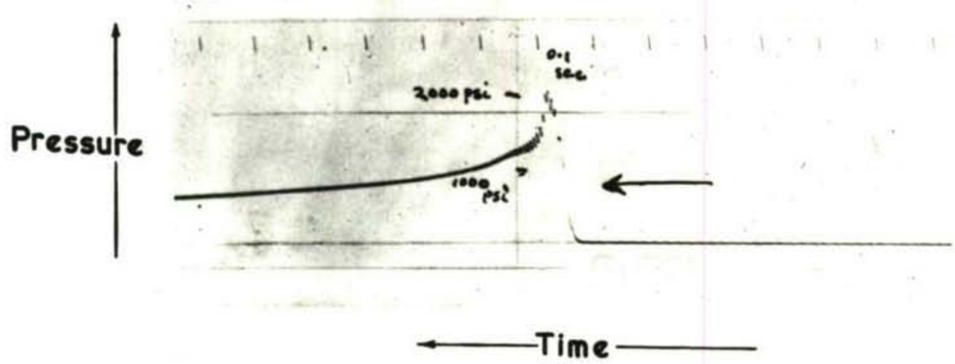


(a) (b)

Fig 10

Effect of Mild Explosion of Ethyl Nitrate in J-Tube

A. Lower End of J-Tube B. Bubble-Stick



Typical Pressure-Time Curve Obtained by Burning Cordite in J-Tube

Fig 11

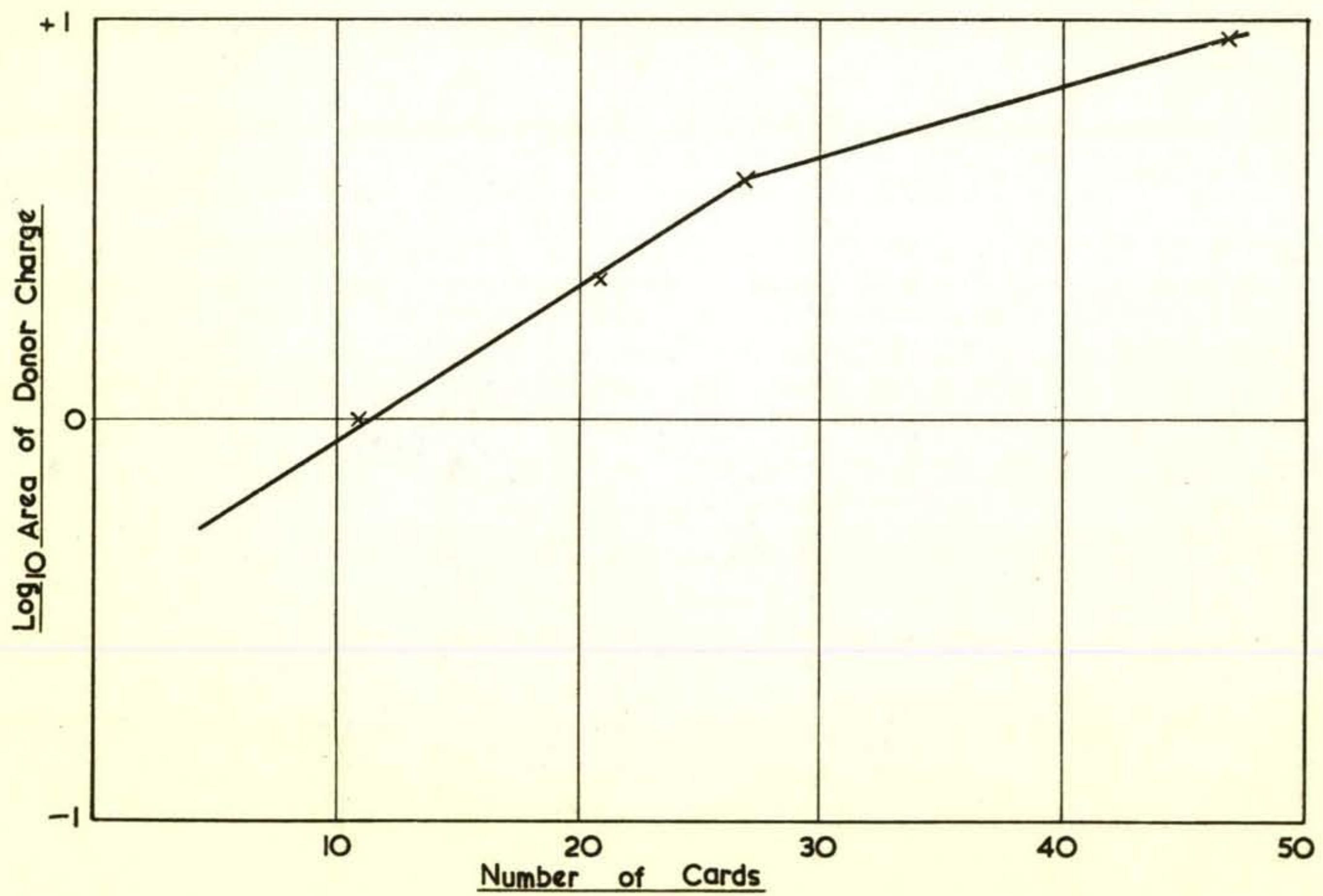


FIG. 12

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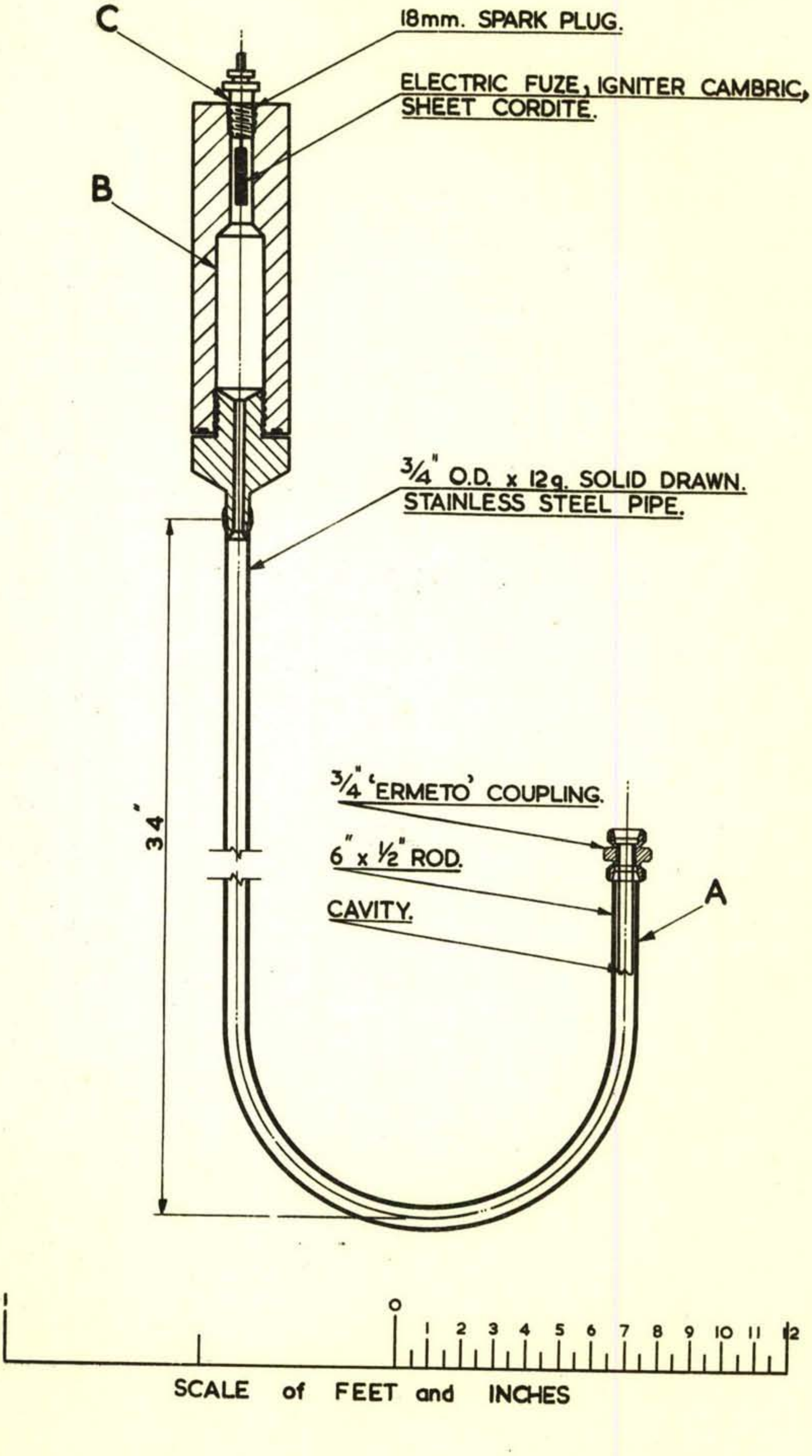

FIG. 13

PRESSURE VESSEL.

MATERIAL: MILD STEEL.

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